Early On-orbit Calibration Results from Aqua MODIS

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ABSTRACT

Aqua MODIS, also known as the MODIS Flight Model 1 (FM1), was launched on May 4, 2002. It opened its nadir aperture door (NAD) on June 24, 2002, beginning its Earth observing mission. In this paper, we present early results from Aqua MODIS on-orbit calibration and characterization and assess the instrument s overall performance. MODIS has 36 spectral bands located on four focal plane assemblies (FPAs). Bands 1-19, and 26 with wavelengths from 0.412µ to 2.1µ are the reflective solar bands (RSB) that are calibrated on-orbit by a solar diffuser (SD). The degradation of the SD is tracked using a solar diffuser stability monitor (SDSM). The bands 20-25, and 27-36 with wavelengths from 3.75µ to 14.5µ are the thermal emissive bands (TEB) that are calibrated on-orbit by a blackbody (BB). Early results indicate that the on-orbit performance has been in good agreement with the predications determined from pre-launch measurements. Except for band 21, the low gain fire band, band 6, known to have some inoperable detectors from pre-launch characterization, and one noisy detector in band 36, all of the detectors noise characterizations are within their specifications. Examples of the sensor s short-term and limited long-term responses in both TEB and RSB will be provided to illustrate the sensor s on-orbit stability. In addition, we will show some of the improvements that Aqua MODIS made over its predecessor, Terra MODIS (Protoflight Model - PFM), such as removal of the optical leak into the long-wave infrared (LWIR) photoconductive (PC) bands and reduction of electronic crosstalk and out-of-band (OOB) thermal leak into the short-wave infrared (SWIR) bands.

Keywords: MODIS, sensor, calibration, thermal emissive bands, reflective solar bands, blackbody, solar diffuser

1. INTRODUCTION

The MODerate Resolution Imaging Spectroradiometer (MODIS) Flight Model 1 (FM1) has been on-orbit for more than 3 months since its launch on-board the NASA Earth Observing System (EOS) Aqua spacecraft on May 4, 2002. The first image of Aqua MODIS was acquired on June 24, 2002 when the instrument opened its nadir aperture door (NAD). MODIS provides close to daily coverage of the Earth in 36 spectral bands with wavelengths ranging from 0.412µ (VIS) to 14.5µ (LWIR) and spatial resolution at nadir of 250m (bands 1-2), 500m (bands 5-7), and 1km (bands 8-36). The Aqua spacecraft crosses the equator at about 1:30 pm (local time), while the MODIS Protoflight Model (PFM) instrument launched on-board the Terra spacecraft on December 18, 1999 is in a 10:30 am equator-crossing orbit. Working together, the two MODIS instruments can view the same area of the Earth in the morning and afternoon, enabling diurnal observations of parameters for global long-term studies of the land, oceans, and atmosphere[1,2,3]. Following a brief review of MODIS on-orbit calibration, we will present Aqua MODIS early on-orbit calibration results, such as detector s noise characterization and response stability. We will also show the improvements made in the Aqua MODIS over its predecessor, Terra MODIS, by comparing the results from on-orbit observations.

2. OVERVIEW OF MODIS ON-ORBIT CALIBRATION

MODIS on-orbit calibrators (OBCs) include a flat panel v-grooved blackbody (BB), a solar diffuser (SD) panel made of Spectralon™, and a spectroradiometric calibration assembly (SRCA). The 16 thermal emissive bands (bands 20-25 and 27-36) with wavelengths above 3.75µ are calibrated on-orbit by the BB with its temperature scale traceable to NIST standards. Calibration of the 20 reflective solar bands is accomplished by using the coefficients derived from SD observations. The BRF of the SD was pre-launch determined with reference to NIST calibrated reflectance samples. An on-board solar diffuser stability monitor (SDSM) tracks any SD on-orbit degradation. The TEB calibration is performed on a scan by scan basis from the detectors response to the OBC BB thermal emission. The RSB calibration coefficients are derived from on-orbit SD observations and stored in the look-up tables (LUTs) for the Level 1B (L1B) calibration and retrieval algorithms. The L1B algorithms convert the instrument response in digital numbers to geolocated and radiometrically calibrated radiance for the TEB and reflectance for the RSB[4]. Figure 1 shows the MODIS scan cavity and the BB and SD, key radiometric calibrators.

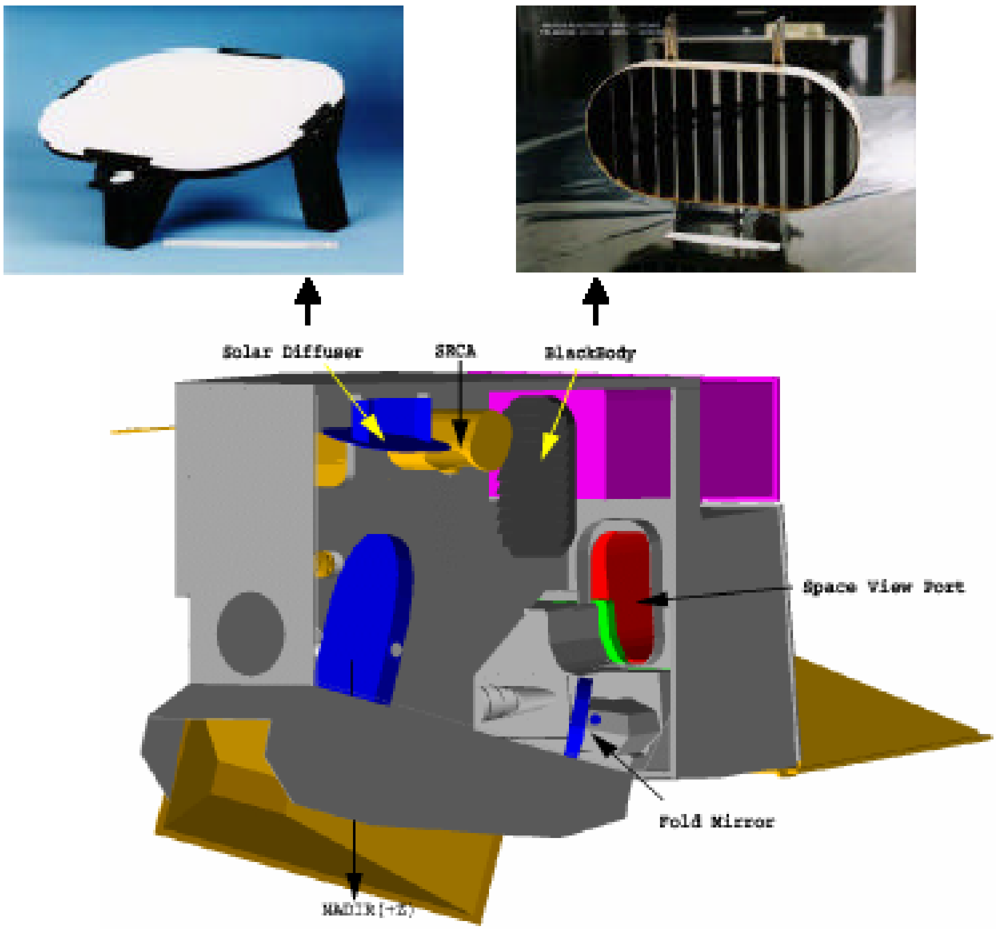

Figure 1: MODIS scan cavity and key on-board calibrators: solar diffuser (SD) and blackbody (BB)

The MODIS TEB calibration algorithm applies a quadratic approach[4]. The offset and nonlinear terms (a_0, and a_2) are provided through the look-up tables (LUTs). On a scan by scan basis, the linear term (b_1, the dominant term) is computed from the sensor s response to the BB emission at a given temperature. Each scan, the sensor views the BB, the space view (SV), and the Earth view (EV). The BB calibration process is expressed by Equation 1,

$$\begin{aligned} &RVS_{BB} \cdot \varepsilon_{BB} \cdot L_{BB} + (RVS_{SV} - RVS_{BB}) \cdot L_{SM} + RVS_{BB} \cdot (1-\varepsilon_{BB}) \cdot \varepsilon_{CAV} \cdot L_{CAV} \\ &= a_0 + b_1 \cdot dn_{BB} + a_2 \cdot dn_{BB}^2 \end{aligned} \quad (1)$$

The LHS of Eqn. 1 is the BB path radiance (L) with instrument thermal background (from the SV path) subtracted. It includes the BB source term, the scan mirror (SM) self-emission term, and the scan cavity emission reflected from the BB. RVS and ε stand for the response versus scan angle and emissivity. The scan mirror term is the difference of scan mirror emission at two different scan angles with different RVS quantities. The dn_{BB} is the sensor s response (digital number) to the BB view with the response to the SV in the same scan subtracted. Similarly the Earth scene retrieval process is expressed by Equation 2.

$$RVS_{EV} \cdot L_{EV} + (RVS_{SV} - RVS_{EV}) \cdot L_{SM} = a_0 + b_1 \cdot dn_{EV} + a_2 \cdot dn_{EV}^2 . \tag{2}$$

L_{EV} is the top of atmosphere (TOA) Earth scene radiance. The calibration is performed for each detector and for each mirror side. Although the linear term, b_1, is calculated scan by scan, a 40 scan running average of responses from each mirror side has been used in the retrieval to avoid any potential jitters from the BB calibration. The temporal stability of the TEB response can be measured by tracking the b_1 variation.

The MODIS RSB primary product from L1B is the Earth scene reflectance factor, $\rho_{EV}\cos(\theta_{EV})$, given by the following expression,

$$\rho_{EV} \cos(\theta_{EV}) = m_1 \cdot dn_{EV}^* \cdot d_{Earth\_Sun}^2 , \tag{3}$$

where m_1 is the reflectance scaling coefficient derived from the SD calibration and dn_{EV}^* is the sensor's Earth view response (digital number) with instrument background and the sensor's response versus scan angle (RVS) effects corrected. The response to changes in instrument temperature is also corrected in dn_{EV}^*. The Earth-Sun distance, d_{Earth_Sun} (normalized to 1AU) is also included. During RSB calibration, currently once per week for Aqua MODIS, the sensor views the diffusely reflected Sun light from the SD. The scaling coefficient for each detector is determined from the SD BRF and the detector s response to the SD, dn_{SD}^*. Thus,

$$m_1 = \frac{BRF_{SD} \cdot \cos(\theta_{SD})}{dn_{SD}^* \cdot d_{Earth\_Sun}^2} \cdot \Delta_{SD} \cdot \Gamma , \tag{4}$$

where Δ_{SD} is the SD degradation factor that is tracked by the solar diffuser stability monitor (SDSM), and Γ is a screen vignetting function for bands (B8-16) that use the SD attenuation screen to avoid saturation. For the bands that do not use the screen, Γ is equal to 1. RSB m_1 is trended for monitoring the detectors response stability. Detailed descriptions of the calibration methodologies and algorithm theoretical basis have been reported by Guenther, et. al.[4,5].

3. EARLY ON-ORBIT CALIBRATION RESULTS FROM AQUA MODIS

3.1 Aqua MODI Detectors On-orbit Noise Characterization

Table 1 summarizes the MODIS reflective solar bands key specifications, including the band center wavelength, typical scene radiance, and the corresponding noise specification. For the reflective solar bands (bands 1-19 and 26), the noise is specified by the signal-to-noise ratio (SNR) at typical radiance. Table 2 shows the specifications for the thermal emissive bands (bands 20-25 and 27-36), in which the noise specification is expressed by the noise-equivalent-difference-temperature (NEdT) at typical radiance or temperature.

On-orbit, the TEB noise is measured from each detector s response to the BB at a fixed temperature over a number of frames and scans and then scaled to the specified typical radiance or temperature. More than one BB temperature setting has been used in the noise characterization. Similarly the RSB noise is measured from the detector s response to the diffusely reflected Sun light from the SD. The on-orbit results of noise characterization are included in both Tables 1 and 2 for comparison with the specifications. Only the center detector of each band is used for illustration purpose. Overall, the instrument noise performance is consistent with pre-launch calibration and predominately within the specifications. The few out of specification detectors seen on-orbit are consistent with pre-launch testing and analyses. For example, B6 had several inoperable detectors (some were noisy) pre-launch. B21 is the low gain fire band that has a much larger uncertainty requirement than that of other bands. The B20 detector 10 (occasionally) and B36 detector 5 are two noisy detectors identified from pre-launch testing. Due to spacecraft safe hold events, Aqua MODIS has transitioned to safe mode from science mode twice during the first three-months of on-orbit operation. There are no additional noisy detectors observed on-orbit since initial on-orbit characterization. Compared to Terra MODIS (results not shown here), the noise performance of Aqua is improved for the long-wave infrared (LWIR) PC bands.

Band	CW (nm)	Ltyp (W/m^2/sr/μ)	SNR (spec.)	SNR (meas.)
1	645	21.8	128	196
2	858	24.7	201	545
3	469	35.3	243	320
4	555	29.0	228	325
5	1240	5.4	74	157
6	1640	7.3	275	495
7	2130	1.0	110	145
8	412	44.9	880	1010
9	443	41.9	838	1400
10	488	32.1	802	1387
11	531	27.9	754	1452
12	551	21.0	750	1263
13L	667	9.5	910	1278
14L	678	8.7	1087	1250
15	748	10.2	586	1230
16	869	6.2	516	1209
17	905	10.0	167	384
18	936	3.6	57	102
19	940	15.0	250	509
26	1375	6.0	150	255

Table 1: MODIS reflective solar bands (RSB) key specifications (center wavelength, typical scene radiance, and signal-to-noise ratio) and Aqua MODIS on-orbit measured signal-to-noise ratio (SNR)

Band	CW (μm)	T_Ltyp (K)	NEdT (K) (spec.)	NEdT (K) (meas.)
20	3.75	300	0.05	0.02
21	3.96	335	0.20	0.21
22	3.96	300	0.07	0.02
23	4.05	300	0.07	0.02
24	4.47	250	0.25	0.11
25	4.52	275	0.25	0.04
27	6.72	240	0.25	0.10
28	7.33	250	0.25	0.05
29	8.55	300	0.05	0.02
30	9.73	250	0.25	0.07
31	11.03	300	0.05	0.02
32	12.02	300	0.05	0.03
33	13.34	260	0.25	0.08
34	13.64	250	0.25	0.12
35	13.94	240	0.25	0.15
36	14.24	220	0.35	0.23

Table 2: MODIS thermal emissive bands (TEB) key specifications (center wavelength, typical scene temperature, and noise-equivalent-difference-temperature) and Aqua MODIS on-orbit measured and noise-equivalent-difference-temperature (NEdT)

3.2 Aqua MODIS Detectors Response Stability

In our study, the sensor s response stability is examined on a scan by scan basis (short term) and trended during on-orbit operation time (long term). For the thermal emissive bands, each detector s response is tracked using the linear response coefficient, b_1 (see Eqn. 1). For B20 and B33, the scan by scan linear coefficients are shown in Figure 2 over a 5 minutes granule of about 100 scans using their responses to the BB from mirror side 1 observations. Only three middle detectors (4-6) have been chosen for illustration. The short-term stability of the Aqua MODIS TEBs is excellent, better than 0.2%.

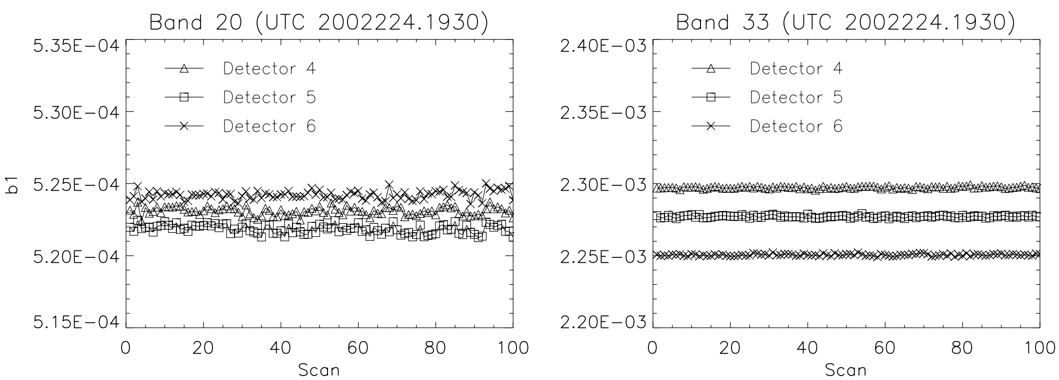

Figure 2: Aqua MODIS TEB detector response (units: W /m^2-µm-sr/count or digital number) versus scan number for bands 20 and 33 (detectors 4, 5, and 6) from 2002224.1930 granule

For the same bands and detectors, the long-term stability is illustrated in Figure 3 using the detectors response trending over the on-orbit operational period. Although the MODIS TEB is calibrated scan by scan, the long-term stability is important. This is because BB values of bands 33, 35, and 36 saturate when the blackbody (BB) operating temperature is above certain limits: 295K for B33 and B35, and 300K for B36. The BB s normal operational temperature is set at 285K for Aqua MODIS. To monitor the TEB offset and nonlinear coefficients stability, the BB performs a warm-up and cool-down cycle (about every 2 to 3 months) with its temperature ranging from 270K to 315K. To keep the Earth view data calibrated when the BB values saturate, an approach has been developed and implemented in the L1B code using calibration coefficients stored in the LUTs. This approach replaces the scan by scan calibration when the BB temperature is above the saturation temperature for bands 33, 35, and 36.

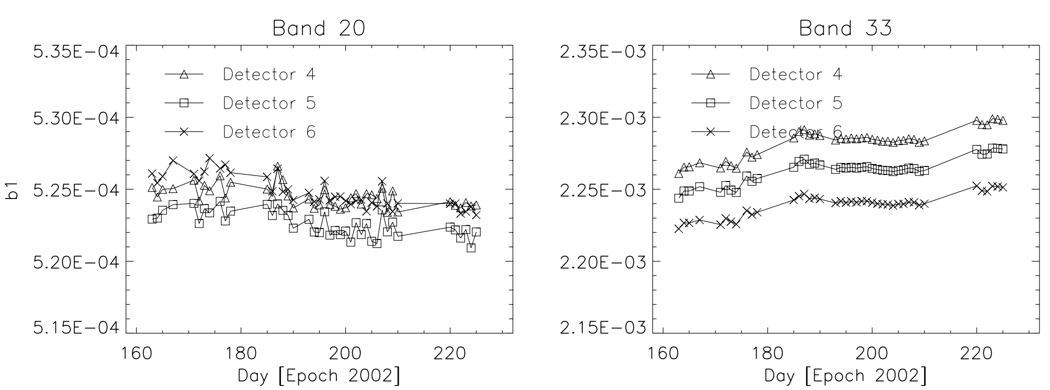

Figure 3: Aqua MODIS TEB detector response (units: W /m^2-µm-sr/count or digital number) versus day of on-orbit operation for bands 20 and 33 (detectors 4, 5, and 6)

It is clear that the TEB response has been very stable in short-term as well as long-term at a given operational condition. The gaps in the long-term trending correspond to the Aqua spacecraft safe hold events that put MODIS in safe mode.

There is a noticeable gain change after each transition back to the instrument science mode, less than 0.5% for B20 and less than 1% for B33. Since the TEB is calibrated scan by scan, the change will not cause any problem. For B33, 35, and 36 that saturate at high BB temperature, the response (or gain) must be stable at each fixed operational condition. When there is a change of response due to an on-orbit event, the LUT containing the coefficients for these three bands will be updated.

For the reflective solar bands, the short-term and long-term stability are shown in Figures 4 and 5 for 3 middle detectors of bands 8 and 18. The RSB calibration uses the coefficients, m_1, derived from available on-orbit SD observations through the use of LUTs. The long-term stability is very important. The Terra MODIS on-orbit characterization has shown some scan mirror degradation in the VIS bands. Therefore, time dependent LUTs are used in the RSB Earth scene retrieval. This requires very stable and/or smoothly varying detector responses.

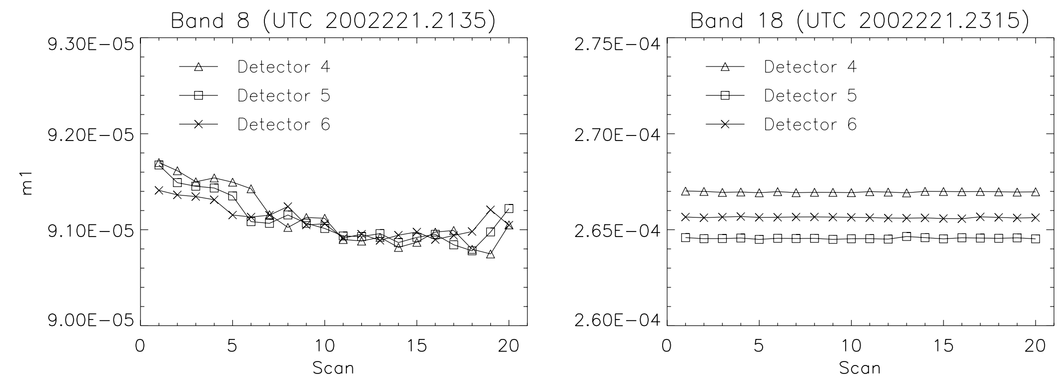

Figure 4: Aqua MODIS RSB detector response (units: 1/count or digital number) versus scan number for bands 8 and 18 (detectors 4, 5, and 6) from 2002221.2135 granule

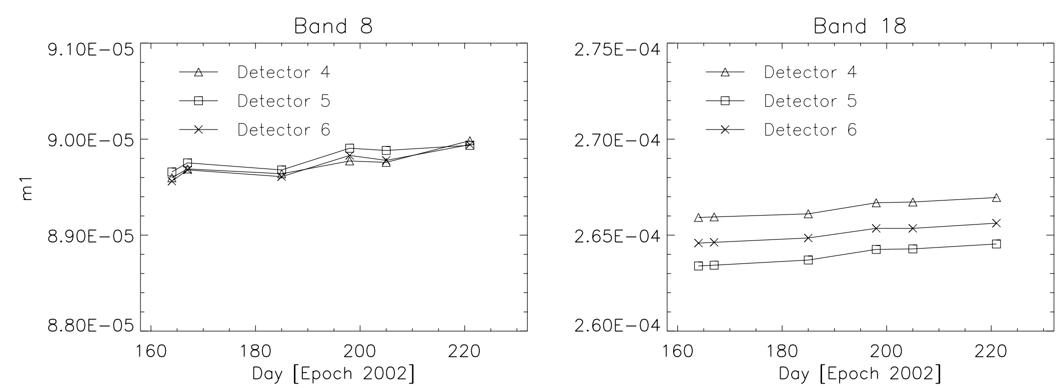

Figure 5: Aqua MODIS RSB detector response (units: 1/count or digital number) versus day of on-orbit operation for bands 8 and 18 (detectors 4, 5, and 6)

It should be pointed out that B8 calibration requires the use of the SD screen (SDS) which causes additional variation in the calibration coefficients. This can be seen from the scan by scan m_1 calculation in Figure 4 (–0.4% variation). B18 does not use the SD screen for its calibration and the scan to scan m_1 variation is very small. The SD calibration is performed at polar regions when the Sun illuminates the SD panel. Only about 20 scans from each mirror side are used for the calibration. When there is no SD calibration activities, the SD door is closed to avoid direct Sun light onto the SD. The degradation of the SD is tracked on-orbit by a solar diffuser stability monitor (SDSM). The results shown in

Figure 4 are before the SD degradation correction. The results in Figure 5 have the SD degradation removed as determined by the SDSM. It s clear that the SD has larger degradation in the short wavelength region (B8: 412 nm).

4. IMPROVEMENTS IN AQUA MODIS

There were a number of improvements made in the Aqua MODIS (Flight Model 1 — FM1) as compared to the Terra MODIS (Protoflight Model - PFM). In the following, two of the improvements, (1) removal of the PC bands (bands 31-36) optical leak that existed in the Terra MODIS and (2) reduction of the out-of-band (OOB) response in the SWIR bands (bands 5-7 and 26), are presented. Other improvements, not illustrated here, include less scattering from the optics, better characterized scan mirror response versus scan angle, and less electronic crosstalk in the SMIR focal plane. Additional examples can be found in a paper by Xiong el. al. [6] in these proceedings.

4.1 PC Bands Optical Leak Removal

It is known that the Terra MODIS (PFM) has an optical leak from B31 to the other PC bands (B32-36) on the same LWIR focal plane. Light from one end of the B31 filter bounces back and forth to other PC bands. This leak can be easily seen in the Terra MODIS on-orbit lunar observations[6]. Figure 6 is an image in the Baja, California area that shows the effect due to an optical leak from B31 to B35 when the scene changes from the ocean to the land or the land to the ocean where there is a sharp temperature difference. The number of frames (or pixels) in the scan direction that show the shadow effect is due to the relative location of these two bands on the focal plane. To correct this effect in the Terra MODIS, an algorithm has been developed and implemented in the L1B code to adjust the instrument response from the BB and from the Earth scene. The crosstalk coefficients from B31 to each of the other PC bands are derived from on-orbit lunar observations. After removing the optical leak, the shadow effect in Figure 6 will disappear from B35 image. This approach has been very effective.

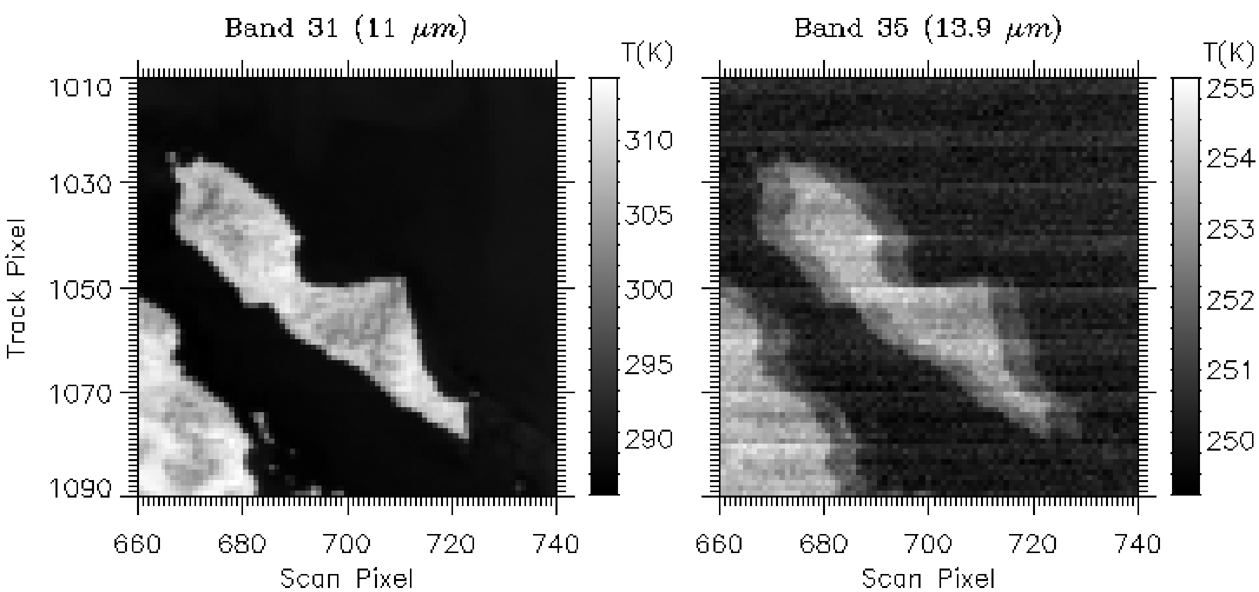

Figure 6: Terra MODIS images (2000078.1835) in Baja, California area for B31 and B35. B31 has no optical leak. B35 has optical leak

Based on the lessons learned from Terra MODIS, this PC optical leak mechanism was removed by adding black paint on the sides of the B31 filter. The effectiveness of this removal can be seen from an Aqua image of the same area as shown in Figure 7. The improvement is obvious.

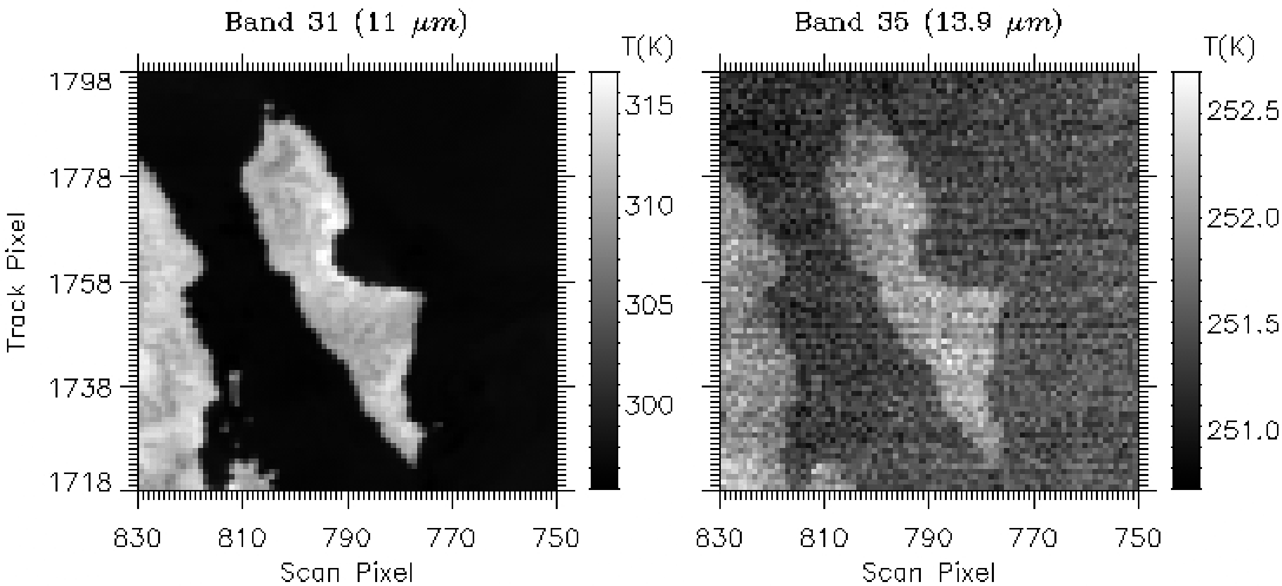

Figure 7: Aqua MODIS images (2002219.2040) in Baja, California area for B31 and B35. Both B31 and B35 have no optical leak

4.2 Out-of-Band Response Reduction in SWIR Band

Another improvement of Aqua MODIS made is the reduction in the SWIR electronic crosstalk and out-of-band (OOB) response. The OOB leak is believed to be coming from 5.3µm thermal emission. The electronic crosstalk causes a difference of the two sub-samples in B5-7. A detailed description of this problem has been given by Guenther, et. al.[5]. For the SWIR bands 5-7 and 26, there should be no earth features from their nighttime images. Because of the OOB leak from the thermal radiation, some of the Earth features can be observed in the nighttime images. In Terra MODIS L1B, a thermal leak correction algorithm has to be added to remove this effect. In Aqua MODIS, the effect is much smaller for B5 and B7. Using the SWIR detectors response to the on-board BB, one can see this OOB response effect, since ideally, there should be no response at these wavelengths when the SWIR bands view the BB.

Figures 8 and 9 show B5 and B7 responses (three middle detectors) to the OBC BB at different BB temperatures for both Terra MODIS and Aqua MODIS. For these two bands, there is a clear reduction in the Aqua MODIS OOB response. The effect in B7 is almost completely gone. The improvement is B5 is also substantial. We did not show B6 since this band has a number of inoperable detectors in the Aqua instrument. There is little change for band 26. The major improvement in Aqua bands 5-7 is the reduction of sub-sample (also called sub-frame) differences. Each 500m resolution band has two samples (frames of data) corresponding to one sample of the 1km resolution bands.

5. SUMMARY

Early Aqua MODIS on-orbit calibration and characterization results have been consistent with its pre-launch testing and analyses. No additional noisy detectors have been found from on-orbit observations. The short-term and long-term (3 month) responses from all the functional detectors have been very stable, allowing high quality on-orbit calibration and data product retrieval. Except for minor problems identified during pre-launch testing, the overall on-orbit instrument performance is excellent, including many of the improvements made over Terra MODIS. In addition to good calibration and characterization from the on-board calibrators, the lunar observations and Earth view data also show improved performance of Aqua MODIS when compared with early Terra MODIS observations. With both Terra MODIS and Aqua MODIS operating on-orbit, many important parameters can be derived for a better understanding of the global land, oceans, and atmosphere.

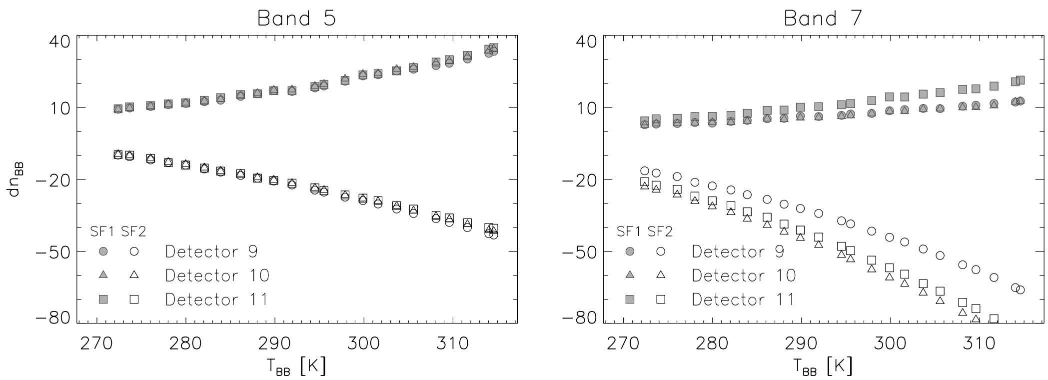

Figure 8: Terra MODIS B5 and B7 responses to the on-board blackbody (BB) from 270K to 315K, showing large thermal leak (OOB response) and substantial sub-frame difference

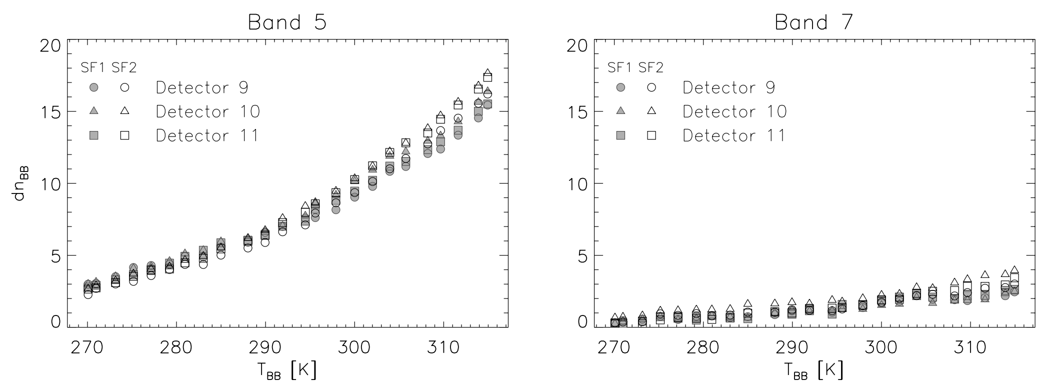

Figure 9: Aqua MODIS B5 and B7 responses to the on-board blackbody (BB) from 270K to 315K, showing smaller thermal leak (OOB response) compared to Terra MODIS and sub-frame difference

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REFERENCES

1. W. L. Barnes and V. V. Salomonson, MODIS: A global image spectroradiometer for the Earth Observing System , *Critical Reviews of Optical Science and Technology*, CR47, 285-307, 1993.
2. W. L. Barnes, X. Xiong and V.V. Salomonson, Status of Terra MODIS and Aqua MODIS , *Proceedings of IGARSS*, 2002.
3. V. V. Salomonson, W. L. Barnes, X. Xiong, S. Kempler and E. Masuoka, An Overview of the Earth Observing System MODIS Instrument and Associated Data Systems Performance , *Proceedings of IGARSS*, 2002.

4. B. Guenther, G. D. Godden, X. Xiong, E. J. Knight, S.Y. Qiu, H. Montgomery, M. M. Hopkins, M. G. Khayat, and Z. Hao, Prelaunch algorithm and data format for the level 1 calibration products for the EOS-AM1 moderate resolution image spectroradiometer (MODIS) , *IEEE Trans. Geosci. Remote Sensing* 36, pp. 1142-1151, 1998.
5. B. Guenther, X. Xiong, V. Salomonson, W. Barnes, and J. Young, On-orbit Performance of the Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) and the Attendant Level 1-B Data Product , accepted for *Remote Sensing of the Environment*, 2002.
6. X. Xiong, J. Sun, K. Chiang, S. Xiong, and W. Barnes, MODIS On-orbit Characterization Using the Moon , *Proceedings of SPIE — Sensors, Systems, and Next Generation Satellites VI*, 4881 (2002).

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